Technical Discussion of the Proposed Shelter ("Alaska") Modification for PM$_{2.5}$ FRM Samplers

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1.0   Background

The specifications for a federal reference method (FRM) sampler for PM$_{2.5}$ are set forth in 40 CFR Part 50, Appendix L. Figure 1 provides a schematic view of a typical FRM sampler. The components that are used to representatively extract, size-select, and transport the PM$_{2.5}$ ambient aerosol (the inlet, downtube, WINS, and upper portion of the filter holder) are specified by design drawings in Appendix L Figure L-1 through Figure L-30. Section 7.3.8 of Appendix L specifies that the inlet intake is 2.0 ± 0.2 meters above the "horizontal/supporting" surface. This distance is a function of the height of the sampler's case, legs, and inlet and the length of the downtube. The ambient temperature sensor is specified to be mounted external to and 5 cm above the horizontal plane of the sampler case (§ 7.4.8.1). A second temperature sensor is specified to monitor the temperature 1 cm downstream of the filter during both sampling and non-sampling modes (§ 7.4.11.1).

Appendix L further defines flow rate control, temperature measurement, and pressure measurement of a FRM sampler by performance specifications. The sampler flow rate is maintained at 16.67 Lpm (1.000 m3/hr) actual volumetric flow rate as measured at the temperature and pressure of the sample air entering the inlet (§ 7.4.1). Section 7.4.10 specifies that the sampler filter temperature be maintained to no more than 5 °C above the ambient temperature. As of spring of 1999, all designated FRM samplers have been designed to achieve this requirement by bathing the components internal to the sampler case in ambient air.

Section 7.4.7 of Appendix L specifies that an FRM sampler should be capable of operating over an ambient temperature range of –30 to +45 °C, a relative humidity range of 0 to 100%, and a barometric pressure range of 600 to 800 mmHg. 40 CFR Part 53, Subpart E specifies the tests required to confirm that a candidate sampler can perform to those specifications. The Subpart E tests specify a temperature range of –20 to 40 °C due to the practical constraints of laboratory testing.

While these tests were designed to cover most, but not all, environmental conditions in the US, the State of Alaska Department of Environmental Conservation has reported many failures of the FRM samplers due to severe cold weather conditions. Discussions with Alaska's Air Quality Staff have indicated that a majority of the failures could be solved by operating the sampler in a shelter in which the temperature is at or above that specified by the regulations. A shelter maintained at a maximum value of –5 °C has been identified as a practical temperature at which satisfactory sampler operation and worker safety can be achieved in a cold weather environment.

The objective of this modification is to maintain high data capture in severely cold weather while maintaining consistency with the national network of $PM_{2.5}$ monitors. The design goals of such a shelter are to:

- keep samplers operational in low temperature environments,

- protect staff during filter change, routine maintenance, and troubleshooting, and

- minimize the necessary hardware and software modifications to achieve the first two goals.

This report presents design alternatives considered, discusses the potential bias resulting from these modifications, and recommends a set of guidelines for shelter usage in severely cold environments.

2.0   Shelter Design

Table 1 presents several alternative shelter types that have been considered to solve the severe cold weather problems. A Type I shelter is a simple modification to existing sampler case design or a second slightly larger case to house the existing sampler's case. The purpose of either approach is to provide insulation, restrict ventilation, and provide heat below an ambient temperature of –5 °C or lower. This simple type of shelter or case modification would likely solve the issue of improving sampler operability; however, does not address the issue of operator protection.

The Type II shelter is large enough to accommodate the sampler, the operator, and additional room to perform maintenance. A similar modification has been proposed for the IMPROVE network to achieve increased data capture in severely cold weather. Figure 2 presents a diagram of a hypothetical 6 ft by 6 ft by 6 ft shelter that would fall into this category. The sampler is installed in the shelter to which a modified downtube is attached such that the sampler inlet is two meters above the shelter roof. This configuration may require wall reinforcement to maintain structural integrity. A roof flange provides the seal to prevent water leakage into the shelter. The ambient temperature sensor is mounted outside of the shelter, to the sampler downtube, at a location that does not interfere with inlet aspiration. A longer cable is necessary to connect the temperature sensor to the sampler electronics. Guy wires may be necessary to support the inlet.

At ambient temperatures above -5 °C, the air inside the shelter must be adequately ventilated to ensure that the filter temperature does not elevate greater than 5 °C above ambient temperature (§7.4.10). A supplemental blower will likely be necessary to force adequate ventilation to achieve this temperature differential requirement. A thermostat would be necessary to cease ambient air ventilation at temperatures below –5 °C. This thermostat would turn on and control a supplemental heater when the temperature in the shelter drops below –10 °C. It is proposed that the temperature inside the shelter should not exceed –5 °C unless the ambient temperature is greater than –5 °C.

A Type III shelter is envisioned to be a larger structure such as those used to house ambient gaseous monitoring equipment. Gas sampling shelters are typically maintained at 20 °C,

which is the minimum operational temperature where gas monitors are operated. It is envisioned that ambient air would need to be ducted to the sampler case, and then exhausted back to the atmosphere. This would likely require an additional blower to move the air through the duct. Additionally, the downtube would need to be insulated to prevent heating during cold weather sampling and to prevent condensation of moisture on internal walls of sampler may occur when the air is warmer outside than in the interior of the shelter. It is believed that the sampler's software would require modifications so that the existing ambient air ventilation scheme would work in concert with the added duct system.

A type II shelter is recommended because it most closely meet the design goals of sampler operation, operator protection, and minimal modification. Type I does not provide any operator protection although this approach represents the most minimal modification. The Type III shelter is an attractive alternative; however, the envisioned modification to existing sampler design necessary to accommodate its use represents substantial departure from the rest of the National Network of $PM_{2.5}$ samplers.

3.0   Potential Bias and Complications Introduced by this Proposed Type II Modification

There are three potential ways that have been considered in which this modification could bias the measured mass concentration relative to a collocated, functional FRM sampler operating in the conventional configuration. First, the shelter itself could influence the manner in which the ambient aerosol is representatively extracted from the atmosphere. Second, aerosol transport losses could occur during transport through the longer downtube. Third, the aerosol could be heated (or cooled) during transport through the downtube as it passes inside the shelter. In turn, this temperature change could cause errors in the reported sampler flowrate and condensation of water vapor onto interior surfaces. This section presents a discussion of these issues and attempts to quantify each where applicable.

Several new modules to an existing Visual Basic program were written to facilitate this task. One module was used to calculate aerosol transport through a downtube of varying length as a function of particle size with diffusion and turbulent inertial deposition considered. A second

module allowed the separation characteristics of the WINS to be estimated for variations in flow rate, temperature, and pressure. A third module was used to integrate downtube transport calculations and changes in WINS separation characteristics with assumed ambient distributions to estimate the resultant mass concentration. The predicted bias introduced due to a particular modification was then calculated as the percent difference of the estimated mass concentration for a new configuration to that of the standard FRM.

The assumed ambient distribution was the FRM "idealized fine distribution" that is presented in 40 CFR Part 53 Subpart F Table F-3. This distribution, superimposed on Figure 3, has a fine particle mode with a MMD of 0.85 μm, a GSD of 2.0, and a mass concentration of 85.0 μg/m^3. The coarse particle mode has a MMD of 15 μm, a GSD of 2.0, and a mass concentration of 15.0 μg/m^3.

3.1   Effect of the Presence of the Shelter on Inlet Aspiration

There are no definitive equations or theories that may be used to calculate the bias introduced by the presence of a bluff body on inlet aspiration. Aspiration of an ambient aerosol is a complex function of wind velocity, particle diameter, inlet geometry, proximity to bluff bodies, bluff body size, and distance of the inlet intake to the ground. In the absence of guiding scientific criteria, the FRM specified a single, wind-speed-independent inlet by design that is to be operated at one flow rate.

Two additional parameters were specified in an attempt to minimize any site and vendor intravariability. One of these parameters is the distance of the inlet intake to horizontal supporting surface. This parameter is fixed in 40 CFR Part 50 Section 7.3.8, which states:

> 7.3.8 Sampling height. The sampler shall be equipped with legs, a stand, or other means to maintain the sampler in a stable, upright position and such that the center of the sample air entrance to the inlet, during sample collection, is maintained in a horizontal plane and is 2.0 +- 0.2 meters above the floor or other horizontal supporting surface.

A second parameter is the separation distance of the inlet intake to the top of the sampler case, which is a function of the physical dimensions of the inlet, the downtube length, and the distance that the downtube extends into the sampler's case. Figure 1 shows that the separation distance from the inlet intake to the inlet exit is 13.5 inches and the downtube maintains 10.5 inches of separation distance between the inlet and the WINS. Figure L-1 further defines that the distance

from the top of the sampler's external case be separated from the WINS by 1 inch ± 1 inch. Therefore, inlet intake to the top of the sampler's external case is a fixed dimension of 23 inches ± 1 inch.

The presence of the shelter introduces a potential bluff body that could adversely affect inlet aspiration. Therefore, as part of this modification, the separation distance from inlet intake to the top of the shelter (S) should be specified in order to minimize variability of this effect. This distance must be kept as possible so that the hardware modifications to downtube length are minimized. Conversely, the bluff body effect should be minimized as the inlet is moved further away from the shelter. One solution is to simply treat the shelter as the horizontal-mounting surface and, therefore, specify that S be 2 meters ± 0.2 meters as in §7.3.8; however, this would require a downtube of approximately 3 meters long. A downtube of this length seems excessive for its intended purpose and may require special wall reinforcement and support.

An alternative is to base S on the maximum width of the shelter. S must be greater for large-sized shelters and does not require modification as the shelter size approaches the width of standard FRM sampler cases. *Therefore, the following equation is recommended:*

$$S \min = 23 inches + 0.5(W - 23 inches) \tag{1}$$
$$S \max = 2 meters$$

where, W is the maximum width of the shelter.

3.2   Aerosol Transport in an Extended Downtube

Extension of the downtube will likely be necessary to accommodate the use of a shelter. Calculation of aerosol transport as a function of particle size and deposition mechanics have been performed to help quantify bias in measured mass concentration that may be introduced due to the longer downtube. In these calculations it has been assumed that aerosol losses due to electrostatic deposition are negligible. This assumption should be reasonable because there is no driving electrical forces that could act on the sampled aerosol. Deposition due to diffusion, turbulent inertia, and thermophoresis will be discussed. Standard temperature and pressure were assumed for these calculations because normal ranges of air properties should have little influence

on predicted outcome. Calculations were performed for various sized downtubes ranging from the standard FRM length (10.5 inches or 27 cm) to 4 meters extra downtube length.

Transport with diffusional deposition considered

The approach presented by Willeke and Baron (1993, page 435, equations (19-19) and (19-20)) was used to calculate aerosol transport through various downtube lengths with diffusional deposition considered. Deposition due to diffusion is a function of particle physical diameter, flow rate, and tube length. Transport was calculated for geometric diameter spherical particles ranging from 0.001 μm to 100 μm. The flow rate used was 16.67 aLpm.

Figure 3 displays the calculated transport of aerosol through the FRM-specified downtube length and extended lengths. Transport is observed to be greater than 95% for particle sizes above 0.02 μm for all additional downtube lengths and rises to above 99% around 0.1 μm. This transport curve was then integrated with the "idealized fine ambient distribution" presented in 40 CFR Part 53 Subpart F Table F-3 to predict overall changes in expected measured $PM_{2.5}$ mass concentration. Table 2 shows that the bias in measured mass is –0.029% for the 3 meter additional length downtube. These aerosol losses would result in a measured mass gain difference of only -0.10 μg for a 15 μg/m^3 mean ambient concentration sampled for 24 hours at 16.7 Lpm. This is comparable to the limit of weighing accuracy with a state of the art microbalance.

Transport with turbulent inertial deposition considered

The aerosol transport of particles through the downtube with turbulent deposition considered was calculated using the approach described by Willeke and Baron (1993, page 99). Figure 4 displays the predicted transport through the FRM specified downtube length and with a 4 meter extension. Transport below 15 μm is greater than 99% for the longer downtube and, therefore, the losses of $PM_{2.5}$ can be considered to be negligible.
Therefore, there should be no effect on the $PM_{2.5}$ mass concentration measurement due to this mechanism.

Transport with thermophoresis considered

A temperature gradient can induce a thermophoretic force on a particle in which the particle has a tendency to be driven from areas of greater temperature to lower temperature. Transport losses can occur due to thermophoretic deposition if the thermophoretic force drives the particle to the wall of the downtube.

In the case of the "Alaska" modification, the winter-time temperature gradient is anticipated to be warm on the outside of the tube and cool on the interior of the tube. This would tend to focus the aerosol to the center of the tube and should not promote increased losses. There are times when the opposite gradient may exist (summer time). This gradient may be considered negligible in shelters of Type I and Type II because they are to be ventilated to ambient conditions resulting in extremely minor potential temperature gradients.

In the Type III gas sampling type shelter, it is envisioned that it could be 40 °C outside and 20 °C inside the shelter. Thermophoretic forces could potentially influence particle transport in this situation. Equations to predict transport through tubes in laminar flow regime are not available (Willeke and Baron, 1993, page 103); however, turbulent equations (equation 6-58 and equation 6-59) were used as a first approximation to estimate the potential bias from this effect. Worst-case conditions were considered where the ambient temperature is assumed to be 40 °C and the shelter temperature is 20 °C. The transport efficiency based on this equation was determined to be 100% for all size particles due to this mechanism. Therefore, deposition due to thermophoresis may be considered to be negligible in this discussion.

3.3 Bias and Complications Introduced by Heating or Cooling the Sample Air

A Type I or Type II shelter will likely require added heat for ambient temperatures below –5 °C. This additional heat could affect the measured mass concentration due to potential flow rate control errors and excessive temperature differential between the filter and ambient temperature. The use of a Type III shelter could cause similar errors due to the air being heated or cooled as it passes through the downtube and to the sample collection filter. The WINS $PM_{2.5}$ separation characteristics depend on the temperature, pressure, and flow rate. Temperature differentials could lead to evaporation or condensation of volatile species or condensation of moisture on the interior surfaces of the sampler.

Draft: third draft

Flow rate control

A presentation of how the WINS separation characteristics are affected by changes in ambient temperature, barometric pressure, and flow rate is necessary to further address potential flow rate control. The performance of the WINS in segregating the $PM_{2.5}$ aerosol from the atmosphere obeys the fundamental impactor relationship presented in Marple and Willeke, 1976:

$$\sqrt{C}D_{50} = \sqrt{\frac{9\rho n\mu W^{3} Stk_{50}}{4r_{p}Q}} \qquad \textbf{(2)}$$

where C is the cunningham's slip coefficient, D_{50} is the impactor aerodynamic cutpoint diameter, n is the number of nozzles (the WINS has a single, round-hole nozzle), µ is the air viscosity, W is the impactor jet width, Stk_{50} is the 50% stokes number from Figure 3 of Marple and Willeke (1976), $_{p}$ is the particle density (equal to 1 g/cm^{3} by definition), and Q is the actual volumetric flow rate through the impactor. W and n are constant for a given impactor such as the WINS. Stk_{50} varies with Reynolds number, but can be approximated to be constant for our range of ambient air calculations. Air viscosity increases as a function of increasing temperature:

$$\mu = 1.81 \times 10^{-4} \frac{g}{cm-s} \left(\frac{T}{293}\right)^{0.74} \qquad \textbf{(3)}$$

where T is air temperature in degrees Kelvin. The slip correction factor, C, is a function of both absolute temperature and pressure and has been empirically derived (Hinds, 1982, p 45, equation 3.20):

$$C = 1 + \frac{\lambda}{D}\left[2.514 + 0.800\exp\left(-0.55\frac{D}{\lambda}\right)\right] \qquad \textbf{(4)}$$

where, λ is the mean free path of air and D is the particle physical diameter. Variation of the mean free path with temperature and pressure may be described by the following equation (equation 3-6 from Willeke and Baron, 1993):

$$\lambda = \lambda_r \left(\frac{101.3}{P} \right) \left(\frac{T}{293.15} \right) \left(\frac{1 + 110/293.15}{1 + 110/T} \right) \quad \text{(5)}$$

where, λ_r is the mean free path at reference conditions (0.0665 μm for air), P is the pressure in kPa, and T is the temperature in degrees Kelvin.

The separation characteristics of the WINS were experimentally measured at standard temperature (293 K) and pressure (760 mmHg) and may be described by its calibrated cutpoint diameter, D_{50} = 2.48 μm, and the geometric standard deviation, GSD = 1.18 (Peters et al., 1999). The dependence of air viscosity on temperature and particle slip on temperature and pressure causes the WINS cutpoint to change due to variations in ambient temperature and pressure even when operated at 16.67 aLpm.

As temperature increases at a given flow rate, air viscosity increases (equation 3) and the particle slip decreases (equation 4 and equation 5) making it more difficult for a particle to move toward the impactor plate, thereby resulting in an increased cutpoint diameter (equation 2). The magnitude of this effect is tabulated in Table 3. The WINS cutpoint at 16.67 aLpm is estimated to be 2.54 μm and 2.26 μm at +40 °C and –50 °C, respectively. An estimation of mass concentration may be calculated by integrating the new cutpoint with the idealized fine distribution (note that it has been assumed that the shape of the separation characteristics, or GSD, remains the same). Table 3 demonstrates that the estimated mass concentration measured increases for increasing temperature as a result of this phenomenon.

As pressure increases at a given flow rate, the mean free path of air is reduced (equation 5) as the air molecules move closer together, which decreases the particle slip (equation 4) again making it more difficult for a particle to reach the impactor plate and an increased cutpoint diameter. The shift in WINS cutpoint with ambient pressure at its design flow rate of 16.67 aLpm is presented in Table 4. The effect is small because ambient pressure affects only particle slip resulting in cutpoint of 2.46 to 2.48 μm at barometric pressures of 600 to 800 mmHg, respectively.

40 CFR Part 50 Appendix L §7.4.1 states:

7.4.1 Sample flow rate. Proper operation of the impactor requires that specific air velocities be maintained through the device. Therefore, the design sample air flow rate through the inlet shall be 16.67 L/min (1.000 m3/hour) measured as actual volumetric flow rate at the temperature and pressure of the sample air entering the inlet.

This statement was written with the intention that the WINS temperature would be within 5 °C or less than the ambient temperature. This will not be true with this modified design, when the temperature of the air is substantially below the temperature of the shelter since it is expected that the sampled air will expand as it passes into the heated shelter. This slightly increase in volumetric flow rate will result in a slightly greater velocity in the nozzle of the WINS, thereby lowering its cutpoint. The magnitude of expansion can be predicted by the following equation:

$$\frac{Q_{WINS}}{Q_{inlet}} = \frac{T_{WINS}}{T_{amb}}\frac{P_{amb}}{P_{WINS}} \tag{6}$$

where T_{amb} is the ambient temperature, P_{amb} is the ambient pressure, and Q_{WINS}, T_{WINS}, and P_{WINS} are the volumetric flow rate, temperature, and pressure in the WINS, respectively. The new WINS cutpoint at this expanded flow rate can then be estimated by using the relationship in equation 1 to form the following equation:

$$\sqrt{C_{new}}\,D_{50}(new) = D_{50}(old)\sqrt{\frac{C_{old}\mu_{new}Q_{old}}{\mu_{old}Q_{new}}} \tag{7}$$

where C is the particle slip correction factor, D_{50} is the WINS cutpoint diameter, μ is the air viscosity, and Q is the flow rate through the impactor. The subscript new denotes the conditions for which the cutpoint is being solved and old denotes the laboratory calibration conditions. Therefore, the D_{50}(old) is 2.48 μm (from the calibration performed at STP), $C_{old} = 1.066$, $\mu_{old} = 1.81$ e-4 g/(cm-s).

A second alternative is to maintain the actual flow into the WINS at 16.67 Lpm by controlling the flow rate at the actual temperature measured with the filter temperature sensor. A comparison of these two alternatives was performed. The WINS temperature has been assumed to equal the filter temperature for these calculations. Additionally, the worst case temperature gradient has been assumed in which the air heats to an internal shelter temperature of -5 °C by the

time it reaches the WINS. P_{amb} and P_{WINS} are assumed to be equal. The estimated mass concentration was calculated by integrating the new cutpoint with the idealized fine distribution.

Table 5 presents a numerical comparison of these two options for flow control. The flow rate into the inlet is held constant at 16.7 Lpm for flow controlled to ambient temperature. The air expands to a new, larger volume as it travels into the shelter for ambient temperatures less than –5 °C. This larger flow rate causes the cutpoint to be reduced; however, a countering effect is that the cutpoint increases due to an increase in air viscosity at the greater temperature (see equation 3). The net effect is that the cutpoint of the WINS at –50 °C was 2.26 μm for a standard FRM (see Table 3) would now be 2.19 μm if the air was heated in the downtube as it passed into the shelter to –5 °C. The estimated mass concentration is 76.505 μg/m^3 for the standard FRM versus 75.727 μg/m^3 for the FRM operated in a Type I or Type II shelter or a –1.07% bias due to the presence of the shelter. An additional observation is that the FRM inside the shelter will likely continue to run and provide data at this low temperature where as the standard FRM is likely to fail.

Alternatively, the WINS flow rate would be held constant if the sampler flowrate were controlled to the filter temperature. The volumetric flow rate at the inlet would become less as the ambient temperature falls below the shelter temperature of –5 °C to compensate for the expanding volume as the air heats in the downtube and WINS. The inlet flow would be 13.9 Lpm as measured at ambient conditions for an ambient temperature of –50 °C and assuming the air heats to a shelter temperature of –5 °C by the time it reaches the sample collection filter. This lower flow rate will affect the aspiration characteristics of the inlet to an unknown extent; however, qualitatively, aspiration should become more wind-speed dependent at reduced flow rates. For this approach, the mass concentration must be calculated by dividing the filter weight gain by the lower volume as measured at the sampler inlet. The cutpoint remains constant at 2.39 μm as well as the estimated collected mass concentration (77.777 μg/m^3) below an ambient temperature of –5 °C by controlling flow to filter temperature. This cutpoint is greater than that of a standard FRM for any given temperature below – 5 °C resulting in a positive bias. This approach would bias the measured mass by +1.7 % at an ambient temperature of –50 °C.

The bias introduced by controlling volumetric flow to the ambient temperature or to the filter temperature is therefore small. Furthermore, adopting control to filter temperature would represent a departure from the existing FRM, wouild certainly involve software modifications,

perhaps require additional hardware modifications, and lead to undefined aspiration issues at the sampler inlet. *For these reasons, it is recommended to maintain volumetric flow control maintained to ambient conditions as specified in the FRM §7.4.1.*

Condensation of water vapor on the interior surfaces of the sampler

Water vapor may condense onto interior surfaces if the temperature of the air is cooled to below its dew point. This water may deposit in the WINS or onto the sample collection filter. Favorable conditions for this to occur should be possible in samplers operated in Type III gas sampling shelters.

4.0   Miscellaneous Issues

4.1   Flags

Table L-1 of 40 CFR Part 53 Appendix L presents a summary of the information that must be provided by the sampler. In this table, data flags are defined for out of specification occurrences of 5-minute average flow rate, 30-second interval filter temperature differential, and elapsed time. These flags are used to invalidate data points.

The heated shelter will certainly cause the 30-second interval filter temperature differential out of specification flag to occur at temperatures below –5 °C. Therefore, it is recommended that a new flag be created to distinguish a 30-second interval filter temperature differential out of specification flags that occurs below –5 °C in a shelter so that this data point is not invalid. Furthermore, it is recommended that the temperature differential flag is not modified above – 5 °C to ensure that the shelter is adequately ventilated.

It is recommended that modification to the flag system be applied subsequent to data collection and not via modification to sampler software. Software modification would cause a sampler in an area with shelter modification approval to deviate from the rest of the national network, and would preclude interchangeability with samplers operated outside.

4.2   Seasonal Use of Shelter

Some discussion has centered upon whether or not the shelter should be allowed for year-round use or restricted to cold weather seasons only. Seasonal restriction would limit shelter operation to the portion of the year during which the sampler would not or may not operate reliably without additional shelter protection. During other portions of the year, the sampler would be installed normally outside the shelter and with its standard, unextended downtube. Each site operator, subject to Regional Office approval, would be required to determine the specific beginning and ending dates for the period of the year during which the shelter is necessary based on local climatic data such as the average mean temperature to establish the earliest and latest date that the local temperature is likely to fall below –20 °C. Difficulties with this approach are that it is difficult to predict beginning and ending dates of shelter necessity and it adds to site maintenance and trouble-shooting during relocation of the sampler. *For these reasons, it is recommended sites with shelter approval be allowed year-round.*

4.3   Leak Check

Section 7.4.6 specifies procedures that must be performed to demonstrate that a FRM sampler does not have a leak. The procedure for external leakage specifies the following:

1. remove the inlet,
2. cap the downtube,
3. turn on the pump and pull a vacuum in the system, and
4. observe the internal pressure over a period of 10 minutes.

It is recommended that this procedure be not modified in any way so that the longer downtube is part of the test.

5.0　　　　Summary of Recommendations

Table 6 compiles the recommendations that have been presented throughout this discussion. We believe that this set of recommendations represents a solution to severely cold weather sampling that will meet the design goals specified at the outset of this document: keep samplers operational, protect staff, and minimize sampler modification.

A Type II shelter which is large enough to accommodate the sampler and the operator is recommended. The separation of the inlet to the roof of the sampler is defined by an equation based on the maximum horizontal width of the shelter in an attempt to reduce the effect that the shelter may have on inlet aspiration. The ambient temperature sensor will need to be relocated to outside the shelter and attached to the downtube. The filter temperature requirement is the same as the FRM until the temperature drops to below –5 °C. Deviations greater than 5 °C above ambient will be considered to not invalidate a sample; however, a new flag shall be established to mark the data for future analysis. The sampler flow rate shall be controlled to the ambient temperature. Lastly, it is recommended that the leak check procedures are not modified in any manner.

6.0　　　References

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Willeke, K., and Baron, P.A. (1993). *Aerosol Measurement*. Van Nostrand Reinhold. New York. ISBN 0-442-00486-9.

Table 1. Shelter types considered to be used to satisfy the goals of the "Alaska" modification.

	Shelter Type I	**Shelter Type II**	**Shelter Type III**
Definition of Structure	slightly larger than FRM case largest case dimension (width, W) < 24 inches	large enough to hold person during filter change – similar shelter proposed for IMPROVE network	typical air quality shelter
Heating Anticipated	heater activates when temperature drops below reliable operating range of FRM (–10 °C)	heater activates when temperature drops below reliable operating range of FRM (–10 °C)	assume inside temperature at a constant 20 °C
Cooling when hot outside or solar insulation is great	need to maintain $T_f > T_a + 5$ °C with ventilation of shelter to ambient temp	need to maintain $T_f > T_a + 5$ °C with ventilation of shelter to ambient temp	need insulated downtube and FRM case ventilation to ambient temperature
Pros	very minimal modification	minimal modification protects crew	
Cons	does not protect staff		more modifications required due to temperature gradient condensation is possible when shelter temperature is below ambient temperature

Table 2. Estimated mass concentration and percent bias versus a standard FRM for various length downtubes due to diffusion deposition. [a]

Configuration	Length of Downtube, cm	Mass Concentration			% Bias Versus Standard FRM
		Fine Mass µg/m³	Coarse Mass µg/m³	Total Mass µg/m³	
Mass existing in atmosphere without fractionation	NA	85	15	100	NA
FRM with standard downtube	27	78.464	0.077	78.541	NA
Downtube plus 1 m	127	78.454	0.077	78.531	-0.013
Downtube plus 2 m	227	78.447	0.077	78.524	-0.022
Downtube plus 3 m	327	78.441	0.077	78.518	-0.029
Downtube plus 4 m	427	78.435	0.077	78.512	-0.037

[a] Assumed aerosol is "idealized fine" as specified in 40 CFR part 50.

Table 3. Effect of variation of ambient temperature on WINS cutpoint diameter.

Ambient Temp °C	Ambient Pressure mmHg	Air Viscosity x 10^{-4} g/(cm*s)	Air Density x 10^{-3} g/cm^3	Reynolds Number	Flow at STP Lpm	WINS D_{50} μm	Estimated Fine Mass Concentration ug/m^3
40	760	1.90	1.12	5360	15.6	2.54	79.004
30	760	1.86	1.16	5670	16.1	2.51	78.777
20	760	1.81	1.20	6010	16.7	2.48	78.541
10	760	1.76	1.24	6380	17.2	2.45	78.296
0	760	1.72	1.29	6800	17.9	2.42	78.041
-10	760	1.67	1.34	7250	18.6	2.39	77.777
-20	760	1.62	1.39	7760	19.3	2.36	77.502
-30	760	1.58	1.45	8320	20.1	2.32	77.119
-40	760	1.53	1.51	8730	21.0	2.29	76.818
-50	760	1.48	1.58	9420	21.9	2.26	76.505

Table 4. Effect of variation of ambient pressure on WINS cutpoint diameter.

Ambient Temp °C	Ambient Pressure mmHg	Air Viscosity x 10^{-4} g/(cm*s)	Air Density x 10^{-3} g/cm^3	Reynolds Number	Flow at STP Lpm	WINS D_{50} μm	Estimated Fine Mass Concentration ug/m^3
20	600	1.81	0.95	4740	21.1	2.46	78.379
20	640	1.81	1.01	5060	19.8	2.46	78.379
20	680	1.81	1.08	5380	18.6	2.47	78.460
20	720	1.81	1.14	5690	17.6	2.48	78.541
20	760	1.81	1.20	6010	16.7	2.48	78.541
20	800	1.81	1.26	6330	15.8	2.48	78.541

Table 5. Comparison of flow rate control using the ambient temperature monitor versus the filter temperature monitor.

Ambient Temp °C	Ambient Pressure mmHg	Filter and Shelter Temp °C	Control flow to ambient temperature as in FRM [a] Inlet flow = 16.7 Lpm			Control flow to filter temperature [a] WINS flow = 16.7 Lpm				Percent Difference %
			Flow at WINS Lpm	WINS D_{50} µm	Est. Fine Mass Conc. µg/m^3	Flow at Inlet Lpm	WINS D_{50} µm	Est. Fine Mass Conc. [b] µg/m^3	Est. Fine Mass Conc. [c] µg/m^3	
0 to 40	760	within 5 °C of ambient	Flow is 16.7 at inlet and at WINS, therefore, no bias between techniques above –5 °C.							
-10	760	-5	17.0	2.38	77.687	16.4	2.39	77.777	76.4	-0.12
-20	760	-5	17.6	2.33	77.216	15.7	2.39	77.777	73.1	-0.73
-30	760	-5	18.4	2.28	76.715	15.1	2.39	77.777	70.3	-1.38
-40	760	-5	19.2	2.24	76.290	14.5	2.39	77.777	67.5	-1.95
-50	760	-5	20.0	2.19	75.727	13.9	2.39	77.777	64.7	-2.71

[a] Worst case heating assumed where air in downtube heats to shelter temperature.
[b] Calculated based on actual volume of air sampled through inlet.
[c] Calculated based on 16.7 Lpm.

Table 6. Summary of recommended modification and performance requirements.

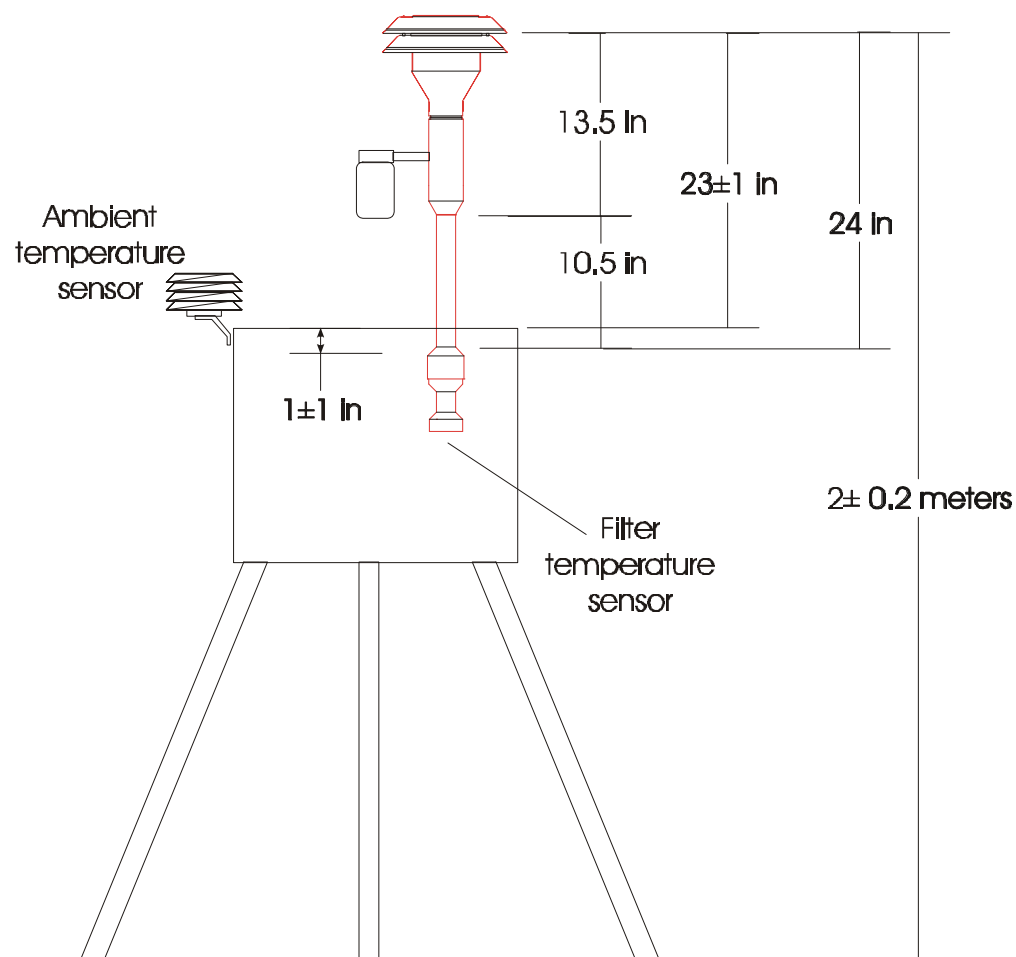| Specification	FRM	"Alaska" Modification
Shelter description	none	Type II
Permitted usage	not applicable	year round
Separation of inlet intake to the roof of the shelter, S_{min}	fixed at 23 inches ± 1 inch	$$S_{min} = 23 inches + 0.5(W - 23 inches)$$
Maximum length of downtube, S_{max}	same as above	$$S_{max} = 2 \text{ meters}$$
Ambient temperature monitor	attached to case	attached to the downtube and outside of shelter
Filter temperature requirement	*for all ambient temperatures:* $T_f < T_a + 5\ °C$	*for $T_a > -5\ °C$* $T_f < T_a + 5\ °C$ *for $T_a \le -5\ °C$* $T_f \le -5\ °C$
Flags	overheat flag if above specification is not met	$T_a > -5\ °C$ same flag $T_a \le -5\ °C$ new flag to indicate that shelter mod caused temperature flag- does not invalidate sample
Flow control	16.67 aLpm controlled to ambient temperature	no change
Leak check	remove inlet and perform leak check	no change

Figure 1. Schematic diagram of a typical FRM sampler.

Figure 2. Schematic diagram of a hypothetical Type II shelter.
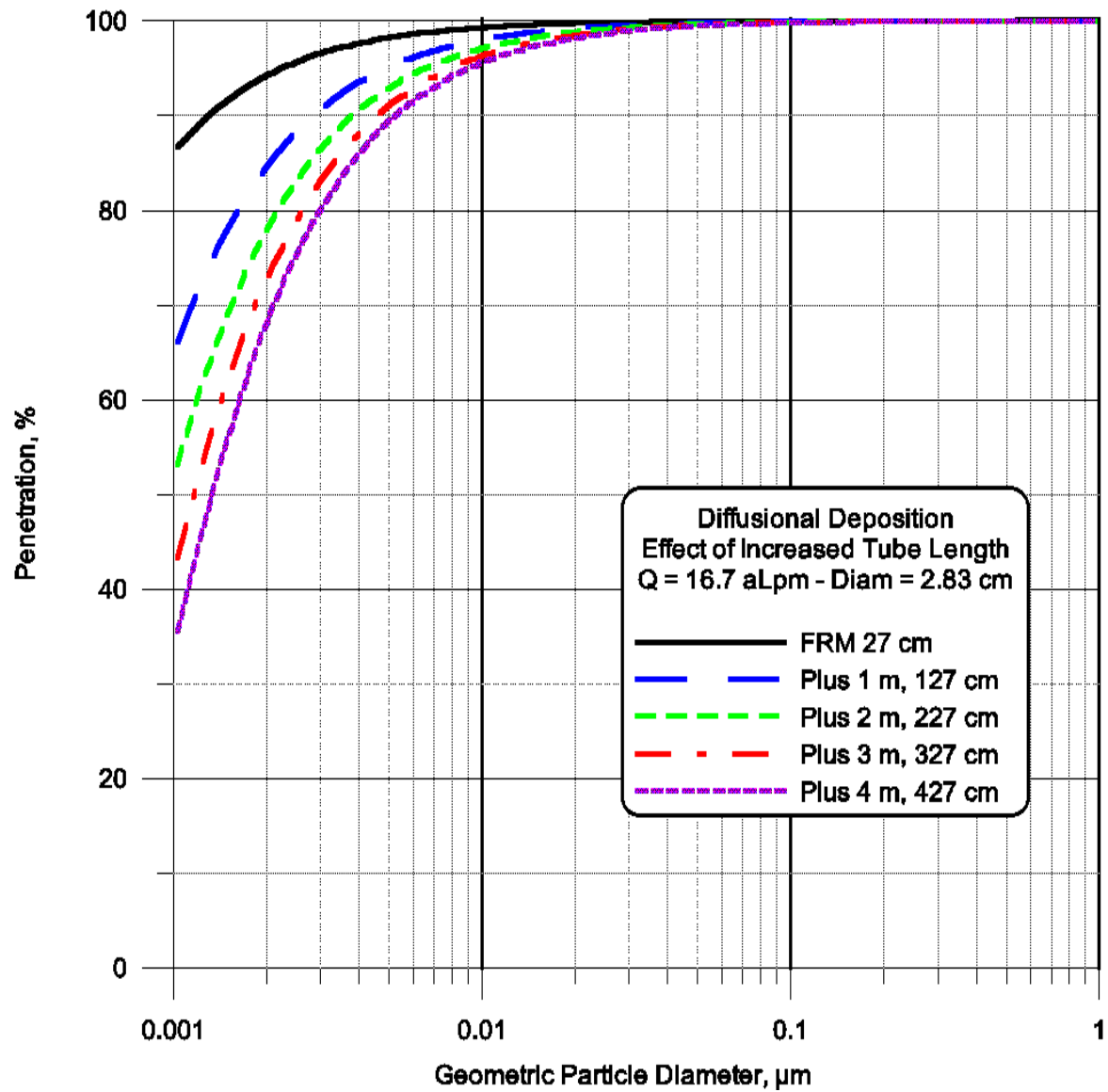
Draft: third draft
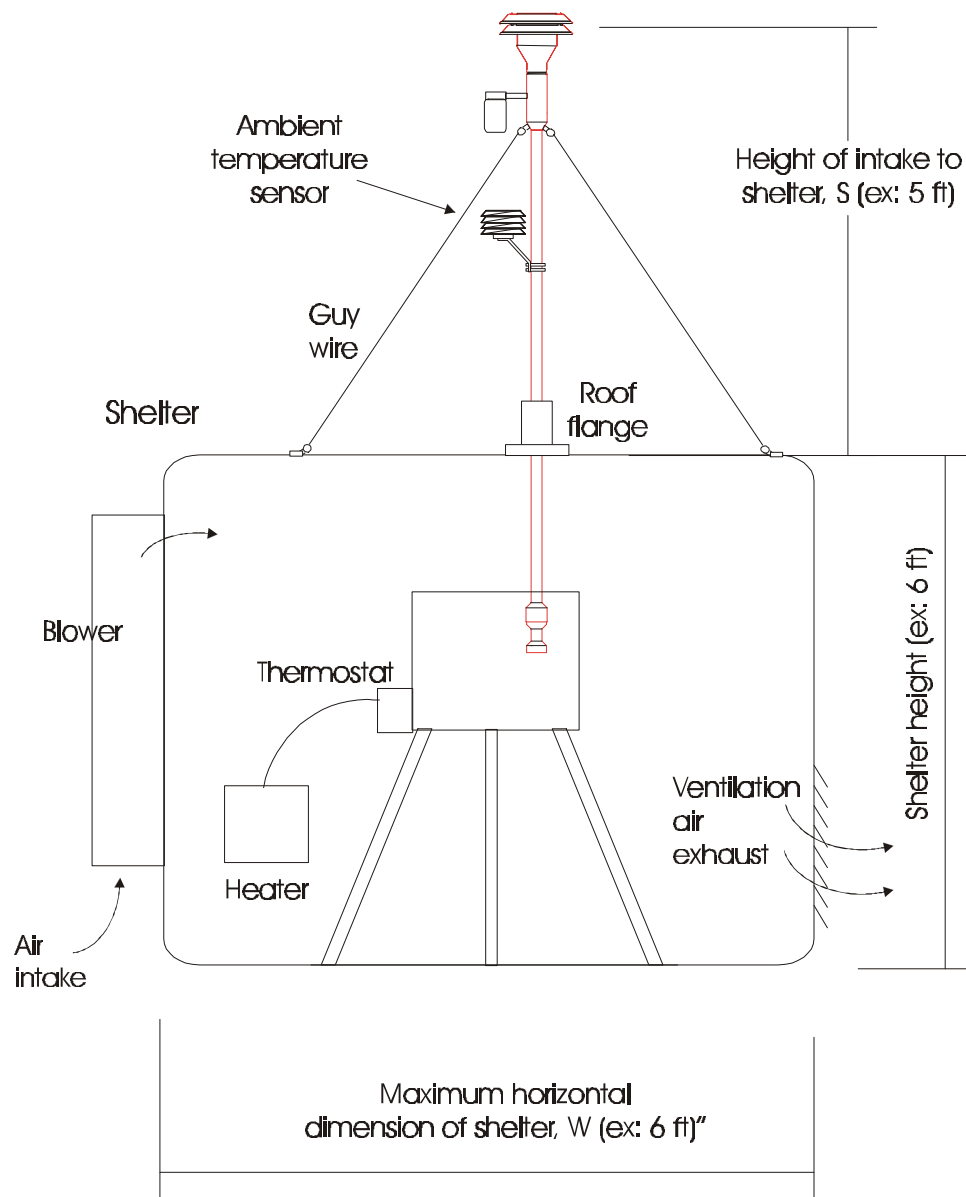
Figure 3. Calculated transport penetration versus particle diameter for various length downtubes - diffusional deposition considered.
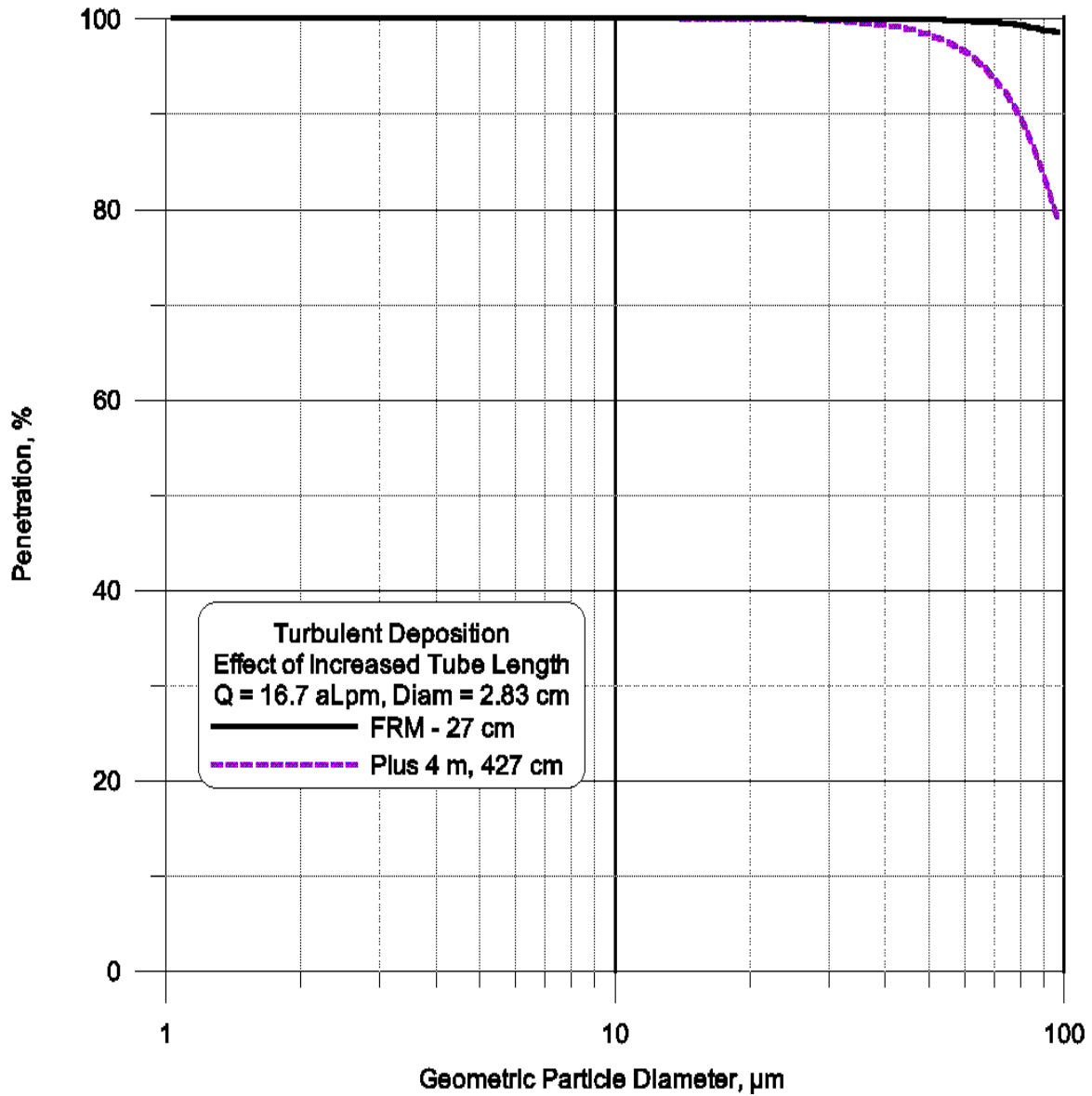
Figure 4. Calculated transport penetration versus particle diameter for various length downtubes - turbulent inertial deposition considered.

Shelter ("Alaska") Modification for PM$_{2.5}$ Samplers

What is it?   A recommended shelter and a "standardized" modification to the inlet system of a federal reference method (FRM) PM$_{2.5}$ sampler for use where it is necessary to protect the sampler (and operator) from severe cold weather conditions. See attached Figure 2 and Table 6 excerpted from "Reference."

Justification   At very cold winter temperatures, FRM samplers may be unreliable unless some cold weather shelter is provided.   (See Supplemental Information, Item #1.)

Sampler and Site Applicability   This shelter modification could be used with any PM$_{2.5}$ sampler that is currently designated by the USEPA as a FRM for PM$_{2.5}$. The modification is intended for use with a designated FRM PM$_{2.5}$ sampler at any monitoring site at which the sampler would not or may not operate reliably without additional shelter protection due to the probable occurrence of severe cold, snow, sleet, ice, or other potentially challenging conditions at the site. The components for the sampler modification (other than the shelter itself), if made available by the sampler manufacturer, would be an approved option included in the reference method designation for the sampler. However, *this shelter modification should be used only where necessary and is subject to approval by the appropriate EPA Regional Office, based on suitably justified need*. If shelter is approved for a particular site, the shelter would be permitted to be used during all seasons of the year, provided adequate ventilation is provided to maintain the shelter interior temperature close to ambient temperature (see "Shelter" below).

OAQPS/ROs: Is this RO approval appropriate? Would some alternative approval be better? Should individual ORD approval be required for each site using the modification also, or instead, of RO approval?

Shelter

The recommended shelter is one about 6 feet high and just large enough to contain the sampler and also allow enough interior room for an operator to properly load and retrieve filters and service the sampler while protected from the weather. A somewhat larger shelter may be needed to accommodate collocated samplers. However, substantially larger shelters should be avoided. (See supplemental information, Item #2.) The shelter must be capable of maintaining an interior temperature of −5 to −10 degrees C whenever the outdoor temperature is −5 degrees C or below, and within 2 degrees C of the outdoor temperature whenever the outdoor temperature is above −5 degrees C. (See supplemental information, Item #3.) This shelter will have to be obtained and installed by the $PM_{2.5}$ monitoring agency, and may or may not be available from the sampler manufacturer.

Sampler installation and inlet height

The sampler should be installed inside the shelter such that an operator can properly service and maintain the sampler. The inlet is extended through the top of the shelter with an extended downtube. To avoid sampling effects from the shelter, the height of the inlet depends on the size (width or depth, whichever is greater) of the shelter (See **Reference** for the rationale). The *minimum* height of the inlet air entrance above the top surface of the shelter (S), in inches, is determined by

$$S_{min} = 23 + 0.5(W − 23),$$

Where W = the width or depth of the shelter, whichever is greater, in inches.

The actual height of the inlet above the shelter may be higher than S_{min}, but it need not exceed 79 inches (2 meters), regardless of the shelter size. The height of the inlet above *ground level* should meet the normal siting requirements for $PM_{2.5}$ samplers. In all cases, the extended downtube must be installed to be vertical, within a reasonable tolerance of about 2 - 3 degrees. No bends or additional downtube components may be used. If required, at least 3 guys should be installed to stabilize the inlet against high winds.

Ambient temperature sensor

The sampler's ambient temperature sensor must be removed from the sampler case and relocated outside the shelter where it will measure outdoor temperature, not shelter inside temperature. It is recommended that the temperature sensor be mounted on the extended downtube about 12 inches below the inlet. The temperature sensor cable should be secured to the downtube to avoid it flapping in the wind. (See Supplemental Information, Item #4.)

Accessories needed

Sampler manufacturers will be encouraged to make available the various accessories needed for installation of the sampler into a shelter. These items would be pre-approved for shelter use. The accessories include at least the following items:

1) **Downtube extension**. One or more lengths of extended downtube to accommodate the inlet height requirements given above. These downtubes will be very similar to the standard 12-inch downtube except for length. (See Supplemental Information, Item #5 for additional information.)

2) **Top or roof flange**. A fixture of appropriate design to facilitate the installation of the downtube through a shelter top or roof. This fixture should include a suitable rain and weather seal or boot, accommodate the vertical load from the weight of the inlet and guys (if used), a feed-through for the temperature sensor extension cable, and any other accommodations that may be necessary to install and facilitate installation of the sampler inlet into the shelter. The fixture is to be designed and installed such that its installation does not change or affect the inside surface or inside geometry of the downtube in any way.

3) **Guy fixture**. A fixture of appropriate design to clamp or otherwise attach securely to the extended downtube at a suitable point to facilitate the installation of 3 or more guys to be used to mechanically maintain the sampler and inlet system in the proper sampling position. The fixture is to be designed and installed such that its installation does not change or affect the inside surface or inside geometry of the downtube in any way. (Guys may not be required for some small shelters.)

4) **Temperature sensor mounting bracket**. Mounting bracket adaptor and associated hardware of appropriate design to facilitate relocation of the sampler's ambient temperature sensor and its sun shield to a secure mounting on the extended downtube at least 12 inches below the inlet. The fixture is to be designed and installed such that its installation does not change or affect the inside surface or inside geometry of the downtube in any way.

5) **Temperature sensor extension cable**. An extension cable (or alternative temperature sensor with longer cable) of sufficient length and appropriate end connectors to facilitate the electrical connection of the sampler's ambient temperature sensor after it is relocated to a position on the extended downtube.

Operation   At ambient temperatures below about –10 degrees C, the measured filter temperature in a sheltered sampler is likely to be more than 5 degrees above the measured ambient temperature, in which case the sampler's filter temperature warning indicator flag will be (automatically) set. It is recommended that such a warning flag *per se* should not result in invalidation of the sample where it can be verified that the flag resulted from collection of the sample in an approved sheltered sampler at ambient temperatures below –5 degrees C, and the sample is otherwise valid.

Supplemental Information

1. **Justification for shelter**. Although the $PM_{2.5}$ FRM sampler is specified for outdoor operation, the range of environmental conditions that it is required to operate over covers most, but not all, potential monitoring sites in the United States. Specifications for operation at all potential U.S. sites would have increased the cost of the sampler considerably, and imposing this additional cost on all sites when the additional capability is required for only a relatively small fraction of the sites could not be justified. Experience during the '98-'99 winter indicated that many of the FRM $PM_{2.5}$ samplers used in the state-operated national ambient $PM_{2.5}$ monitoring networks and SLAMS network experienced a variety of operational problems of increasing frequency as minimum ambient temperatures fell below about –5 to –10 degrees C and particularly below about –14 degrees C. Some of these operational problems have been corrected or ameliorated by manufacturer-developed hardware or software changes to the sampler. However, many of these problems remain and can be expected to recur during the '99-'00 and subsequent winters. These operational problems include failure of pumps to start, loss of liquid crystal data display, leakage of seals, malfunction of filter exchange mechanism, and increased viscosity or crystallization of WINS impactor oil. Further, these low temperature ranges, coupled with typical wind chill factors, present a substantial hazard to the safety of sampler operators, who must load and retrieve filter cassettes and service the samplers. To help insure reliable sampler operation and achieve reasonable data completeness, it is therefore imperative that a sampler shelter maintaining a minimum temperature of about –5 to –10 degrees C be employed for the FRM sampler at sites that typically experience temperatures below that range for many days during the winter season. The shelter would also provide some protection from ice and snow. Although such a partially heated shelter may increase the loss of some volatile components, it is believed that such losses will be minor and acceptable when the alternative is likely to be a lost or voided sample because of sampler malfunction. See also the **Reference** for a technical discussion of particle losses and sampling error analysis regarding the recommended sampler modification.

2.   **Shelter size**. Smaller shelters could be considered but would not offer protection to the sampler operator and may restrict access to the sampler for proper servicing. Operator protection is important because some sampler operations require substantial time, require the dexterity of bare hands, and/or require protection from wind. Larger shelters heated to 20 degrees C or more, as are typical for gaseous pollutant monitoring, are specifically not recommended for $PM_{2.5}$ samplers because of the fairly extensive modifications to the sampler that would be required to maintain proper temperature conditions for the sample filter(s) and the possibility of moisture condensation under some circumstances (see **Reference** for additional discussion on shelter size).

3.   **Shelter temperature control**. In perhaps the simplest shelter temperature control, the shelter could be equipped with both an electric heater and a ventilation fan. The heater should be of sufficient heat capacity to reliably maintain the temperature inside the shelter at a minimum of -5 degrees C during the coldest outdoor temperatures expected at the site. A thermostat for the heater should be set to maintain control of the inside shelter temperature in the range of approximately -10 to -7 degrees C whenever the outdoor temperature is below that range. A small interior fan may be required to distribute the heat evenly inside the shelter. The ventilation fan should be of sufficient CFM capacity to maintain the shelter interior temperature within 2 degrees C of the outdoor temperature whenever the outdoor temperature is above -5 degrees C. A simple thermostat should turn on the fan at any shelter temperature above approximately -3 degrees C and turn off the fan at any shelter temperature below about -5 degrees C. A more sophisticated differential fan thermostat would turn on the fan only when the shelter temperature exceeds the outdoor temperature by approximately 1.5 degrees C. In either case, the shelter should have inverted U-shaped ventilation ducts or automatically closing louvers to conserve shelter heat at temperatures below -5 degrees C. Care should be used in adjusting the two thermostats so that no condition will cause both the fan and heater to be on at the same time. Of course, more elaborate shelter temperature control systems could also be used. Filtering of the ventilation air should be considered to reduce interior dust buildup, provided adequate ventilation flow rate can be maintained.

Note: These temperature control limits may be difficult to obtain, and wider limits may have to be implemented. These limits would not be mandatory requirements, and shelter interior temperatures would not be required to be monitored (although that certainly would be encouraged). However, any filter temperature warning flags (over 5 degrees C above ambient temperature) that occur at ambient temperatures above -5 degrees C would be valid, and their frequency of occurrence must be kept very low.

4.   **Measurement of outdoor temperature**. Relocation of the temperature sensor outside the shelter is necessary to preserve the measurement of true outdoor temperature and allow the sampler to maintain and record the correct sampler volume at outdoor conditions for calculation of the $PM_{2.5}$ mass concentration. At outdoor temperatures significantly below -5 degrees C, the sample air will likely warm somewhat as it enters the portion of the downtube that is inside the shelter. This will cause some increase in the volume flow rate of air in the WINS, which will shift the cut-point of the WINS slightly. Calculations show that this shift is negligible with respect to the slight shift in WINS cut-point that occurs with reduced temperature, and both effects result in an insignificant error in the $PM_{2.5}$ concentration measurement. (See **Reference** for details of this analysis.)

5 **Downtube**.   The extended downtube, designed to connect between the sampler and the inlet to replace the standard 12-inch downtube, should be of the necessary length to raise the inlet to the requisite height above the shelter. The extended downtube shall be fabricated according to Figure L-19 of 40 CFR 50, Appendix L, except that the length is longer than the specified 12.00 inch length dimension. Any variances approved in the design or fabrication of the standard downtube for a particular sampler would also apply to the extended downtube. Note also per Figure L-19 that the outside diameter of the downtube may be varied somewhat to accommodate standard-size tube stock, provided the downtube wall thickness is sufficient to maintain suitable structural strength of the part for its intended application. If various lengths of downtubes are made available by the sampler manufacturer, not more than 2 such lengths should be joined together to obtain the required minimum inlet height above the shelter.

Reference

"Technical Discussion of the Proposed Shelter ("Alaska") Modification for $PM_{2.5}$ FRM Samplers," report, available from Frank McElroy (919-541-2622, fax 919-541-1153).
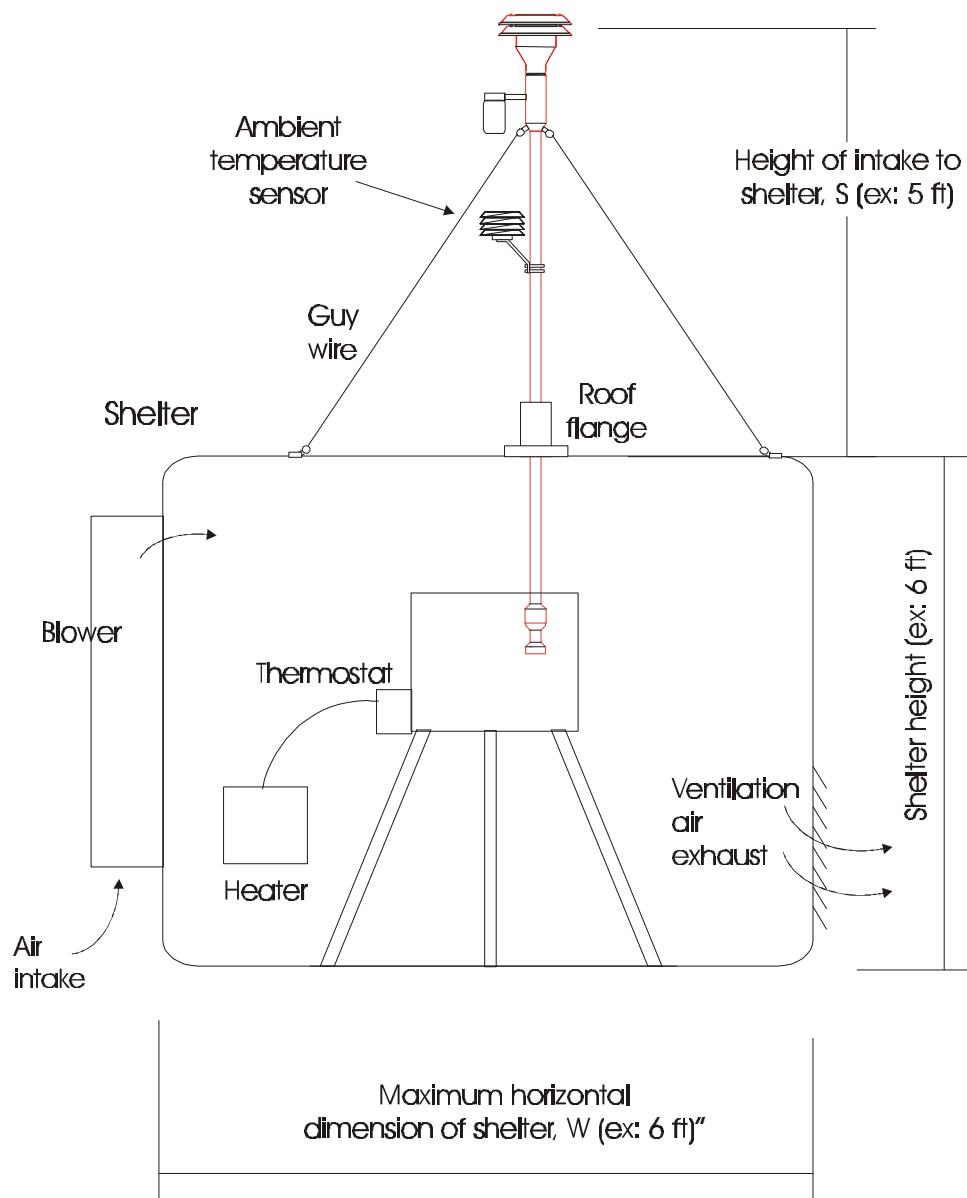
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Figure 2. Schematic diagram of a hypothetical Type II shelter.

Table 6. Summary of recommended modification and performance requirements.

Specification	FRM	"Alaska" Modification
Shelter description	none	Type II
Permitted usage	not applicable	year round
Separation of inlet intake to the roof of the shelter, S_{min}	fixed at 23 inches ± 1 inch	$S_{min} = 23\,inches + 0.5(W - 23\,inches)$
Maximum length of downtube, S_{max}	same as above	$S_{max} = 2\ meters$
Ambient temperature monitor	attached to case	attached to the downtube and outside of shelter
Filter temperature requirement	*for all ambient temperatures:* $T_f < T_a + 5\ °C$	*for $T_a > -5\ °C$* $T_f < T_a + 5\ °C$ *for $T_a \leq -5\ °C$* $T_f \leq -5\ °C$
Flags	overheat flag if above specification is not met	$T_a > -5\ °C$ same flag $T_a \leq -5\ °C$ new flag to indicate that shelter mod caused temperature flag- does not invalidate sample
Flow control	16.67 aLpm controlled to ambient temperature	no change
Leak check	remove inlet and perform leak check	no change